

## **Relation between structure and morphology in the development of the granite cave of "O Folón" (Vigo, Galicia-Spain)**

### **Relación entre estructura y morfología en el desarrollo de la cueva granítica de "O Folón" (Vigo, Galicia-España)**

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#### **Abstract**

O Folón is a subterranean pseudokarstic system developed in granites. The cavity has been developed in several stages dynamised by the active eustatic changes of the end of the Caenozoic in the western coast of Galicia, NW Spain. The system evolution starts with the subedaphic weathering of the rock through the discontinuities. The water circulation by the fissural system produces the emptying of alterite that infilled it. This process firstly begins in the superficial zone of the massif while the weathering continues in the lower levels. The appearance of voids among blocks allows its resetting. Outside this produces exo pseudokarstic forms (doline type) and inside collapse forms (chaos de boules) infilling the voids. The charge concentration on the contact points among blocks generates scallops, pressure scales or onglets. At first, the water flow at low velocities allows the generation of rills or the deposit of speleothems, essentially flowstone, bell canopy and varved deposits. As water flow increases its speed, there appear forms of mechanical erosion (pot-holes). The relative unevenness of the subterranean system, 34 m, is close the one of the change in the base level of the zone, 60 m. The difference is due to the scarce capacity of the waterflow that drains by the O Folón system to erode the rock. 905 m of galleries and passages, mainly fossil conduits, were mapped including 235 m of active subterranean flow. The development of the cavity is adapted to the massif fracture systems with two main orientations: subvertical diaclases and subhorizontal shear planes. The morphology of the conduits is of phreatic and vadose type with transition forms among them, very similar to the ones described for carbonate rocks. The use of complex projections, plant detail, longitudinal profiles and cross-sections allows the reconstruction of the cavity evolution during the network incision. The cross-sections have been elongated vertically up to the external geomorphologic surfaces close to O Folón, thus enabling to associate the evolution of the cave with the regional geomorphologic history.

**Key words:** pseudokarst, granites, mechanical erosion, edaphic weathering, speleothems, vadose and phreatic circulation, base level.

## INTRODUCTION

O Folón Cave, located in the village of Fragoselo-Coruxo, council of Vigo (Galicia, Spain) (Fig. 1a) [UTM: 519939E, 4670444N], is a pseudokarstic granite system boulder cave related to Late-Hercynian fracture. Tubes and pipes appear to be formed by erosion carried out by water of the materials derived from the rock weathering (VAQUEIRO, 2003). Table 1 summarizes the main topographic data for this cave.

The cave system was developed by the continued incision of the da Rega River from the surface +100/+120 m.a.s.l of Plio-Pleistocene geomorphologic age (VIDAL ROMANÍ, 2002) (Fig. 1b).

Like in karstic systems s.s. (VENI, 2005), in the granitic massifs the pseudokarstic systems are developed according to fractures and diaclosed planes where permeability is greater. These planes and fractures guide the development and evolution of the conduit network of O Folón as the base level is modified. The

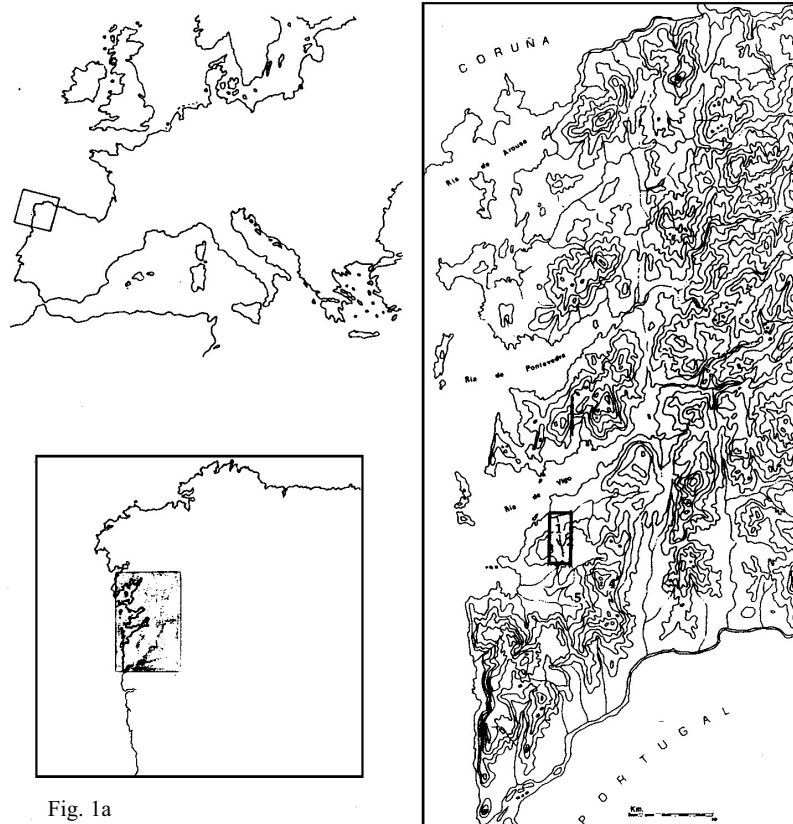
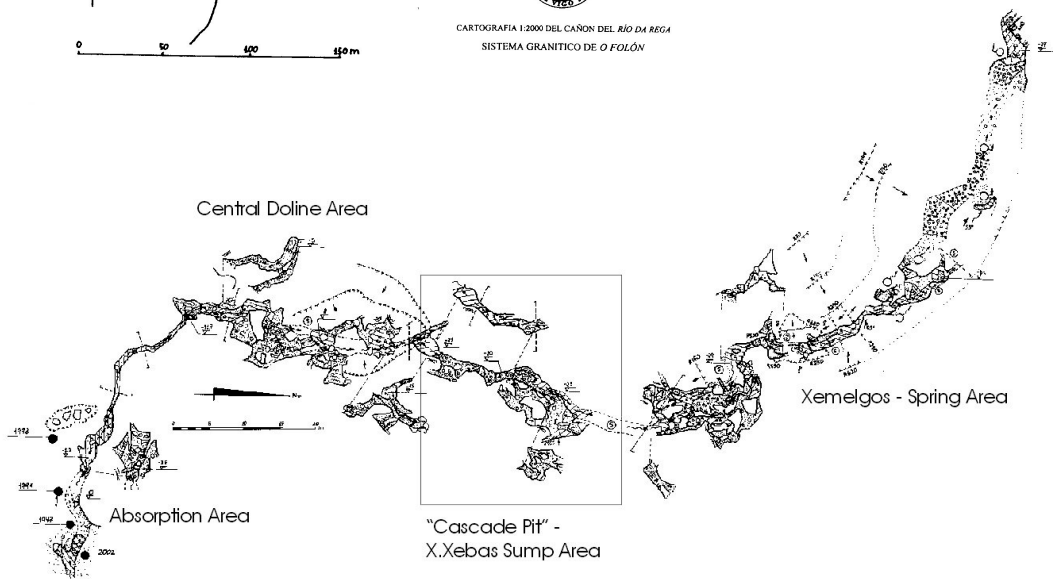
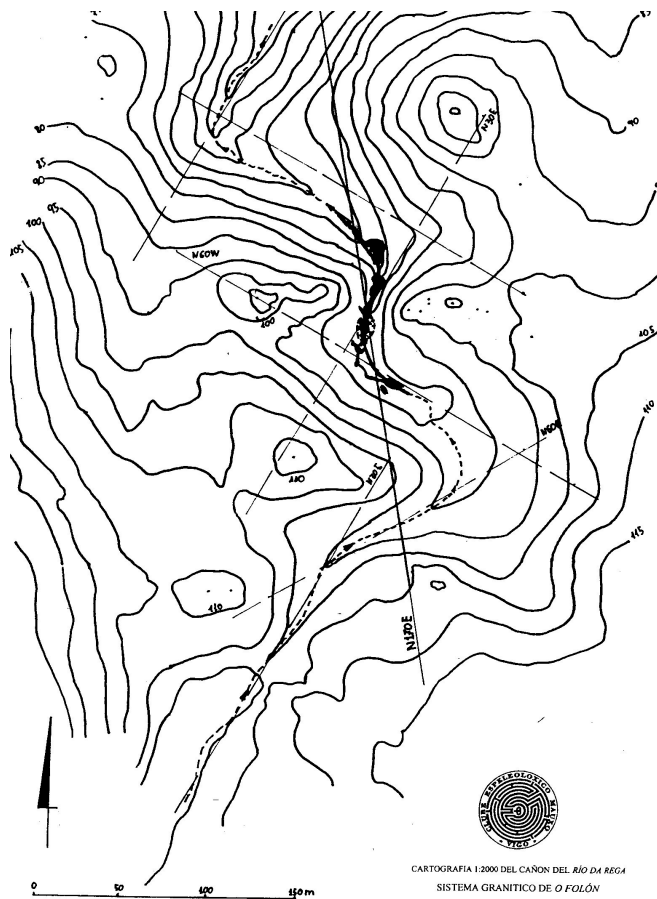


Fig. 1a

Fig. 1. Location maps for the area that are being studied. To the right canyon detail and fracture sets which have determined the O Folón System Cave structure and the pattern of passages. The system is being developed by the recursive cutdown of the river Río da Rega which had started from the paleo-surface of +100 m.a.s.l. / +120 m.a.s.l.

Below the plant view on survey cave, locating the passage from "Cascade Pit" to "X.Xebas Sump", in the X.Xebas Cave.



enlargement of the fracture network allows the opening of voids each time greater and at greater depth in the rocky massif. The big mechanical resistance of the granites ( $\geq 1500 \text{ kg/cm}^2$ ) enables the development of big vaults though with smaller heights than in limestone. With certain dimensions, depending on the rock resistance, the collapse of the conduits is produced with accumulation of blocks generated in the lower spaces. In surface the movement of blocks will give rise to subsidence doline.

In the granites the dissolution does not control the process like in karstic zones *s.s.*, and the lateral migration of the subterranean rivers in the regolith free conduits is essentially produced by physical erosion. The capacity of these processes is less than in the karst of soluble rocks due to the greater resistance of the rock and its insolubility. But it is also possible to establish a geomorphologic sequence to reconstruct the process with certain detail.

As indicated above, weathering in granitic rocky massifs only developed when a variation in the base level is produced. In O Folón, its closeness to the general base level (coastline) enables to relate its evolution with the one of the Vigo Ría during the same time stage. The process develops at about the beginning of the Cainozoic, though especially during the Quaternary, due to the eustatic changes related to the glacial and interglacial stages of the Pleistocene. The incision associated to the changes of the base level, however, is closely adapted to the massif structure (essentially formed by a system of horizontal and vertical or subvertical planes). Therefore, the longitudinal profile of the O Folón pseudokarstic

system is represented by a succession of rocky steps over which the present network flows (VIDAL ROMANI, 2002).

In O Folón there are distinguished four big granitic steps which are, from top to wall, the following: The *Absorption-Central Doline* area, the *Central Doline* area, the *Cascade Pit-X.Xebas* Sump area, and the *X.Xebas Sump-Spring* area.

The circulation of the da Rega River, which drains through O Folón in its present subterranean section, presents very variable features. In the present channel the abandoned inactive sections alternate with other partially infilled by moved blocks and with still active sections. In case of the fossil or abandoned sections it would be difficult to reconstruct the original outline if there were not preserved forms like pot-holes and fossil micro-channels, or varved deposit infillings and other sedimentary forms typical of endokarstic environments.

In this work there are described the features of the present flow and of the paleo-channels located between the Central Doline and the sump of X.Xebas (Fig. 1c).

This section has been selected due to two reasons:

- The cave conduits are narrow and vertical, preferably enlarged along the subvertical pseudo-foliation developed after the shear band.
- The accessible conduits of this sector have been relatively preserved intact in an wide zone located between the surface and the local sump (from -10 to -23/-25 m with respect to the *Absorption area*).

|   |           |
|---|-----------|
| Total length of surveyed passages           | 904.93 m  |
| Total length of the water carry             | 235.39 m  |
| System depth (measure over the water carry) | -34.20 m  |
| Length of the water carry sump              | 84.93 m   |
| Total meters surveyed from 1992-2006        | 1632.13 m |

Table 1. Topographic information.



## SYMBOLOLOGY AND REFERENCES

There is not an adequate legend that represents the granitic forms and even less in the case of subterranean environments. To solve this, an adaptation of the existing nomenclature is proposed in this work and, when necessary, there was made a proposal of new symbols. The nomenclature used herein is based on four types of legends:

- Cave symbols, edition 1999, from the official UIS Symbol List, by Survey and Mapping Working Group, UIS Informatics Commission at the International Union of Speleology. (They can be found in one of these web pages: <http://www.uisic.uis-speleo.org/wgsurmap.html#symbols> or <http://www.carto.net/neumann/caving/cave-symbols/> ).
- Cave symbols list, edition 1992, from the official FEE Symbol List. (MARTÍNEZ I RIUS, 1992)
- Geomorphologic symbols for the "Mapa geomorfológico de España" (MARTÍN-SERRANO et al., 2004).
- New symbols designed for this work: some "official" symbols have been used, extending their meaning. In these cases the new meaning for the symbol was detailed in italics.

Table 2 contains the list of used symbols. In the topographic works of cavities, the symbols of plan and profile could vary but in general the geomorphologic symbols are the same in both cases.

The height of the steps and the depth of the pits are indicated in centimetres, avoiding decimals.

The topographic data given by the Clube Expeleológico Maúxo have been compiled between 1992 and 2006 and they were: First version 1992-1997 (CEM, 1997, 1998); second version, reviewed and redesigned (GROBA et al., 2002 a and b); third version that includes the second doline and the sump-spring area (VAQUEIRO, 2004); and the final

geomorphologic topography including complete cross-sections, surface channels and special profiles (VAQUEIRO, 2006).

The cartography presented herein enables to correlate present and fossil forms and graphically represent the genesis and evolution of the subterranean system of O Folón in a simple manner.

Archaeological levels have been used as chronological reference and also to indicate accessibility to the cave during prehistoric times. Nevertheless, the exact location of archaeological sites is not indicated to protect them from sacking.

## CHARACTERISTICS OF THE CONDUITS

The conduits and the morphologic features that characterise them (pot-hole, fluvial polish surfaces or lateral sapping) may be partially buried by sediments (terraces, varved sediments) or even result inaccessible for the chaos de boules produced by the collapse of the vaults. In general, when the conduits use a vertical or subvertical fracture they present a morphology of vadose type with an cross-section enlarged in the vertical and very narrow. When the subterranean network moves in favour of subhorizontal structural planes or with small dips, the cross-section of the channel is wider giving a morphology similar to phreatic conduits. This is due to the hardness and insolubility of the material excavated there, especially if it is compared to the equivalent processes in classic karstic environments. The mechanical erosion associated to the water flow and its charge of sediments (it cannot be spoken of dissolution though existing in microscopic or centimetre scale) are concentrated at the bottom of the conduit and on the base of the lateral walls normally polished. Other frequent forms of mechanical erosion are the ones produced by the action of boulders giving rise to pot-holes, pseudo-scallops and crescentic scars by impacts of boul-

ders among them or against the conduit walls. In some cases several superposed sections of galleries may appear confirming the network incision caused by changes in the base level.

Figures 2a and 2b represent a series of cross-sections of conduits of the studied zone. There the morphologic features aforementioned are indicated: lateral notches, paleo-channels, pot-holes and other forms of mechanical erosion and formation of speleothems.

The only waterfall existing in O Folón is developed in the intersection of two fractures with directions N30°E and N160°E (VAQUEIRO, 2003). The lateral vadose conduits in the

upper part of the "*Cascade Pit*" may be interpreted as an abandoned anastomased channel when the water enlarged the pit after cutting down the surface of the upper conduit. Water has excavated there a subvertical incise gutter in the surface over which it flows. It is a plane with orientation 75° N 270E.

In this zone the erosion forms are located between -10 and -15 m below the *Absorption* area. Paleo-levels have been mainly identified based on the lateral notches at the bottom of the channel and pot-holes tilted by the block movement where they developed or simply by remains of pot-hole.


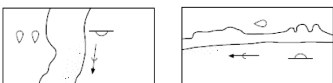
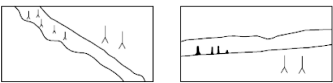
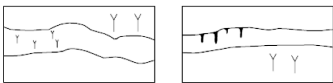
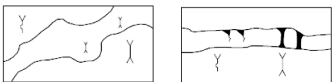


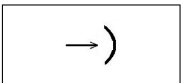
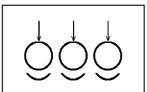
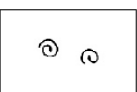
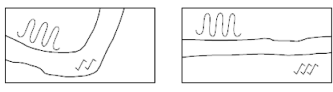
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|--|---|---|--|
| SPRING – SINK<br>                           |   | SCALLOPS – FLUTES IN GENERAL<br>DIRECTION OF PALEOFLOW AND PALEO-LEVELS<br> |  |
| STALAGMITES<br>                            |   | STALACTITES<br>  |  |
| SINTER CURTAINS – PILLARS<br>             |   | CAULIFLOWER – CALCITE DISK – CORALLOIDS AND BOTRYOIDALS<br>               |  |
| WEATHERING FORMS (TAFONI, GNAMMA,...)<br> |   | LATERAL NOTCHES<br>   |  |
| ONGLETS<br>                               | POTHOLES<br> | ANASTOMOSEN – KARREN<br>  |  |

Table 2. Morphological symbols used to reference special cave features. Note that cursive format indicates an extension of the meaning of any pre-existent symbol.

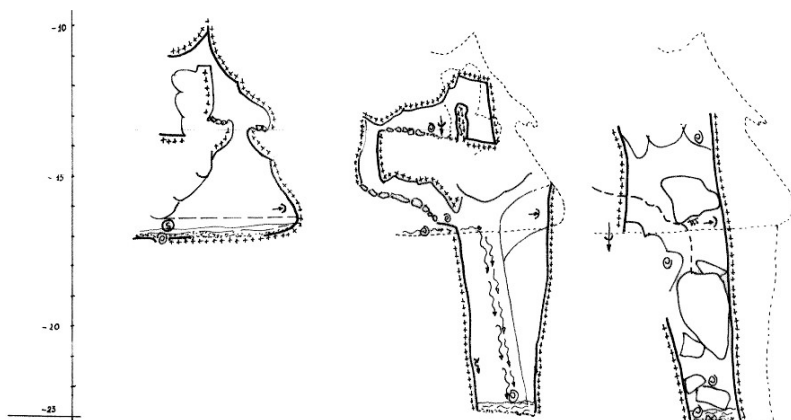


Fig. 2a

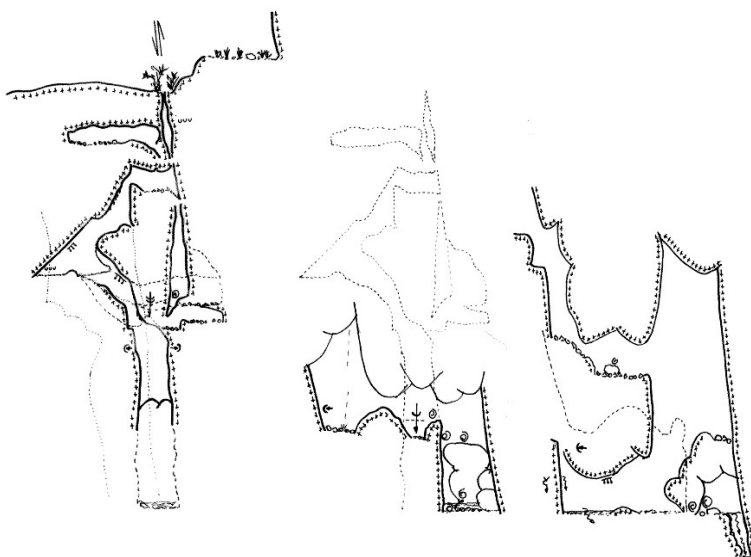


Fig. 2b

Fig. 2. Succession of the topographic cross sections elaborated in the area which is being studied. The waterfall had been developed at the intersection of two fractures with directions N30°E and N160°E, and this one is directly related to the main subvertical shear band which determines the cave passage pattern (VAQUEIRO, 2004). Vadose lateral passages at the top of “*Cascade Pit*” may be anastomose channels abandoned when water lengthen the pit by cutting down the surface of the passage. In these area erosion forms, enclosing residual, removed, and disarticulated fragments of potholes, and lateral notches are located between the elevations -15 and -10 m below the *Absorption area*. Waterfall is characterized by the narrow incised subvertical gutter which is emplaced into the wall and guided by Y-planes. Dot line indicates the emplacement of the previous cross section. In the succession represented above. Notches, paleo-flows, erosion forms like potholes and speleothems (pigotite draperies and opal botryoids) are indicated in the different cross sections. In the four sections (from the left), the paleo-surface +120 m.a.s.l. is located above +45 m over the subterranean river. The cave structure is over the 40% of the canyon dept

The vadose conduits have notches on their bottom that use the existence of horizontal discontinuities. Its profile is asymmetric which may be due to structural reasons (different orientations of the discontinuities). These notches have rough surface which may be due to either a short water circulation along them

or a later weathering. They have been represented in figures 3a and 3b.

Figures 3c and 3d correspond to complex profiles formed by the coalescence of different undercutting fronts transversal to the channel development. They are located between levels L2 and L3.

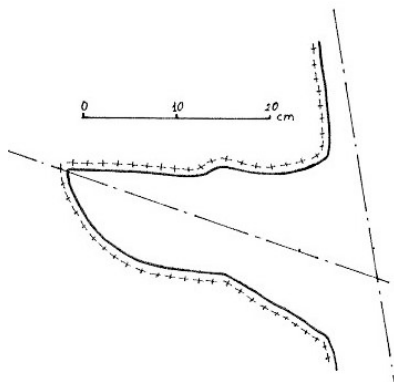


Fig. 3a

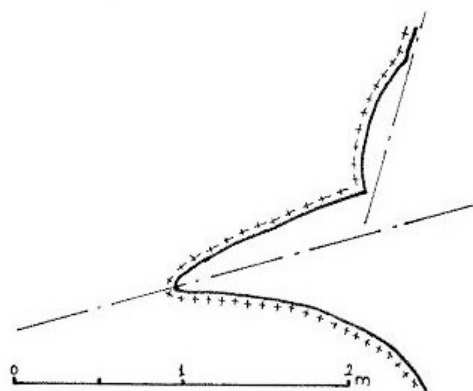


Fig. 3b

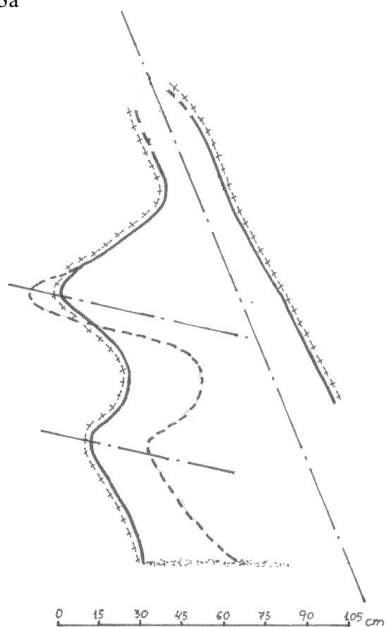


Fig. 3c

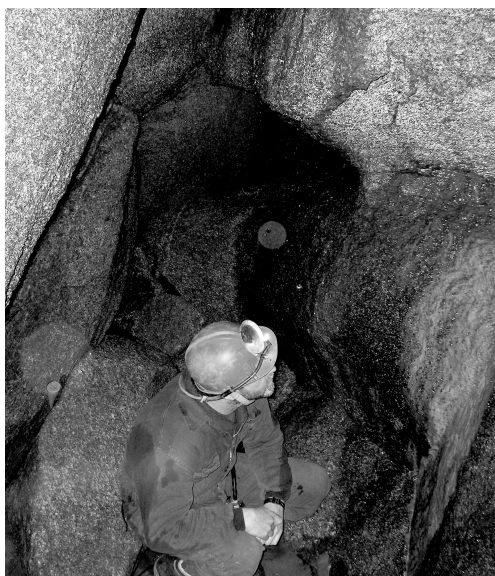


Fig. 3d

Fig. 3. Many different notches and their relation to structural fractures. They have been located in paleo-levels. Note that subhorizontal notches are not symmetrical.

Picture: A complex cross section formed by the coalescence of different dipping notches between L2 and L3.



Fig. 4a

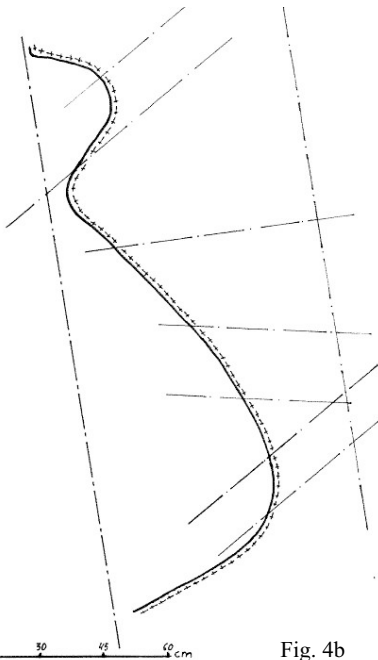


Fig. 4b

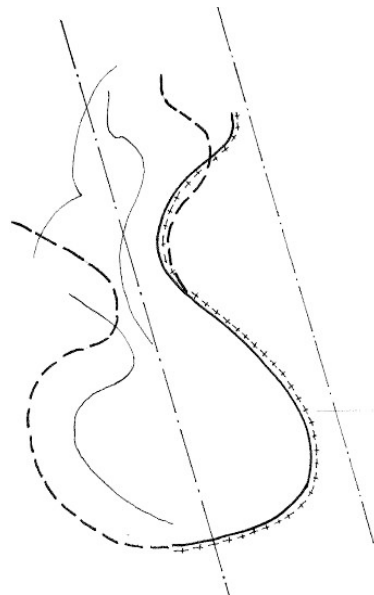


Fig. 4c

Fig. 4. A cross section of an incised passage developed under phreatic conditions. At present passage is partially collapsed and removed. It permits us the measure of diagonal and dipping fractures. The conduct have been reconstructed from disarticulated fragments.

In the picture, a part of this phreatic-incised conduct can be seen beyond the caver.



Fig. 5a

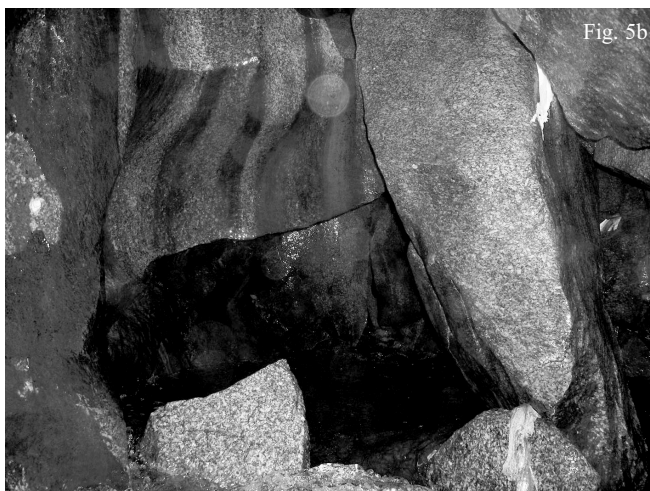


Fig. 5b

Fig. 5. To the left, many onglets have been developed along the subhorizontal limit between corestones in the transition from the L2/L3 paleo-levels to L4. These forms appear to be like scallops (pure erosional form in vadose passages), but they derive from local structural overloads which produce rock weathering.

When vadose or phreatic passage is developed, the weathered rock is removed by water flow. The form is polished during vadose evolution of the passage. Below, many vadose conducts including potholes and other erosional forms from level L4. The picture at the center is the rockslide which collapsed the stepped transition between L3 and L4 levels. The collapse have developed the ending sump area in this cave.

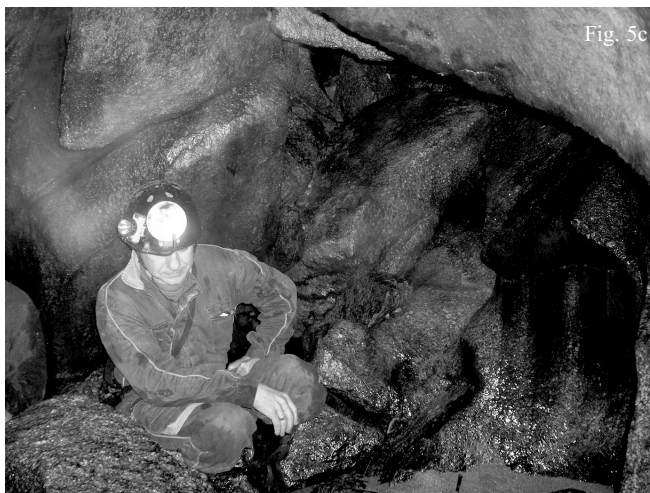


Fig. 5c

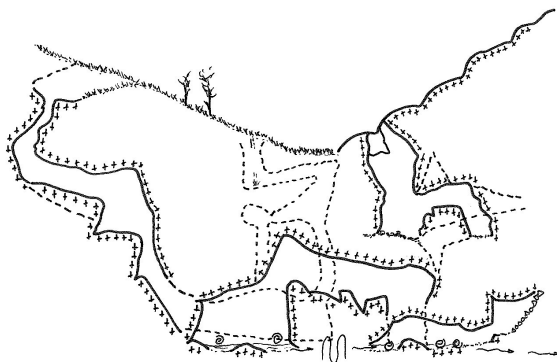


Fig. 6a

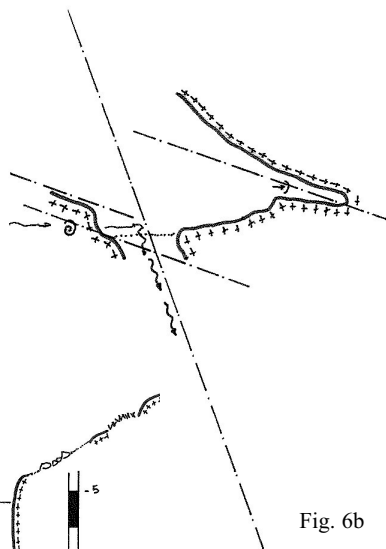


Fig. 6b

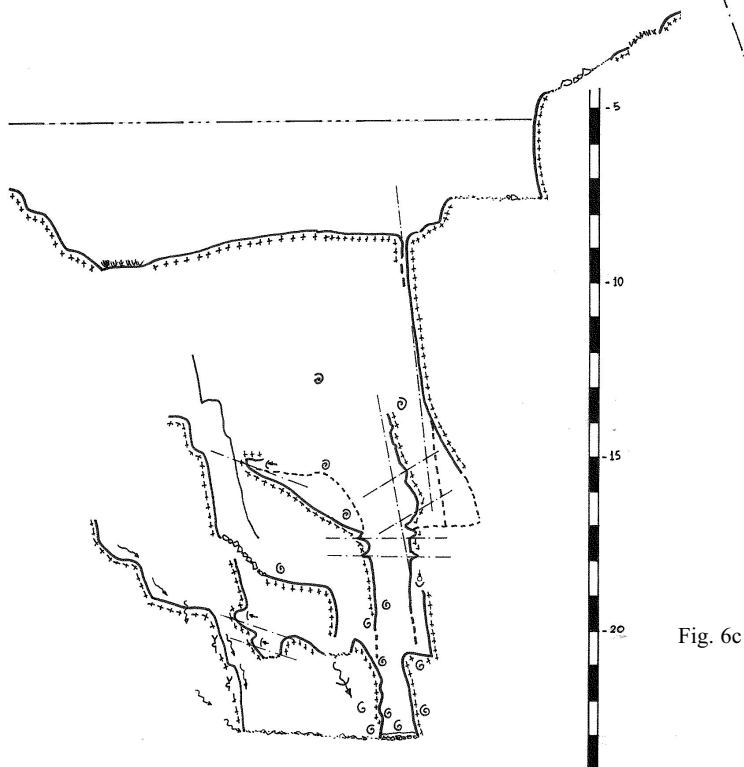


Fig. 6c

Fig. 6. Three complex cross sections elaborated from the survey data. All sections are in their own real elevation below the “*Absorption Area*” to visualize the correlation between the incised surfaces. To the left: It can be observed the present structure of this system underlying the *Central Doline*. Upper line remarks the limits of this doline. At center: The cross section of the waterfall head. The maximum water level at the present is remarked with dot line and flow marks. It are indicated the dipping planes and fractures from which lateral notches and incised gutter have been started out. To the right: This plot was made by the superposition of many individual cross sections in which disarticulated blocks were virtually removed looking only for rocky continuous surfaces. Previous dipping surfaces and paleo-flows are then remarked. They area indicated the incised-phreatic passages preserved in paleo-flow levels overlying the lateral notches which limit the incised-vadose gutter, and the potholes and disarticulated potholes in their real positions and elevations.

In the transition from paleo-level L2/L3 to level L4, some onglets or pressure scales (fig. 5a) have been developed on the border of the big blocks that form the walls of the main flow. These onglets or pressure scales are convex forms developed by charge concentration on the contact points between moved blocks and the cavity walls or even in other blocks.

Some conduits present elliptical or circular sections (fig. 4a). Generally, the ellipses are of oblique axis with elongation according to the subvertical shear plane 75° N270°E (Y-plane), though they may be influenced by other subhorizontal discontinuities (0, +/-10, +/-20°) (fig. 4b). The walls of these conduits are polished and in some cases are symmetric with respect to the fault plane. One of these conduits is represented in figure 4c.

These conduits have complex sections formed by interference of several elliptical tubes of different dimensions. The resulting forms do not coincide with the "keyhole" sections (incised phreatic conduits) typical of the karst, but the existence of elliptical sections seems to indicate that each level in these conduits has been initially developed under phreatic conditions.

Figures 6a, 6b and 6c correspond to three complex sections. The first shows the present structure of the system below the Central Doline (collapsed structure). Its upper line highlights the limits of the doline and is used as reference for the other two. The second section (fig. 6b) corresponds to the waterfall drainage divide. The maximum water level at present is represented by the dotted line with the flow symbol. There are indicated the dipping of planes and fractures where the lateral notches and the waterfall channel incision start from. The third section (fig. 6c) has been constructed by superposition of several individual sections where the blocks have gone back to their theoretical original position trying to so reconstruct the disposition of the rocky wall at that moment. In the old conduits it is marked the lateral notch that limits the vadose and

incise channel. The pressure scales, complete pot-holes or their fragments are marked in their corresponding position and at their real elevation.

## DISCUSSION

The da Rega River is a secondary course of the network that drains through the Vigo Ría.

As the sea level changed during the Plio-Pleistocene, the phreatic level goes down to lower levels and increases the hydraulic gradient. This produced the change in the water circulation regime through the system of conduits from phreatic to vadose and finally the incision of the channel bottom.

This incision process successively left hanging the older levels of the system generating new ones and modifying the hydraulic gradient and, therefore, the erosion capacity of the water.

As the walls of the conduits were eroded and lateral notches were produced, the new surfaces interfered with other fractures of the system. One consequence of this erosive process is the release of the block system through which the system of conduits flows, fragmenting or even destroying them completely making it lose its capacity of water flow which had to look for another way. In some cases the blocks even moved hid the original morphology of the conduit (fig 5b).

The evolution of the cavity is shown in the profile of fig. 7 where it may be observed the present disposition of the system between the Central Doline (the great collapse) and the ending sump X.Xebas Cave. This sump is produced by a block slide that fell on the present channel (level L4). The way of this course has been indicated with flow symbols. When the blocks and the residual blocks or boulders are big, though the original disposition had been altered, the resulting conduit may even preserve drainage capacity in conditions similar to the original ones.



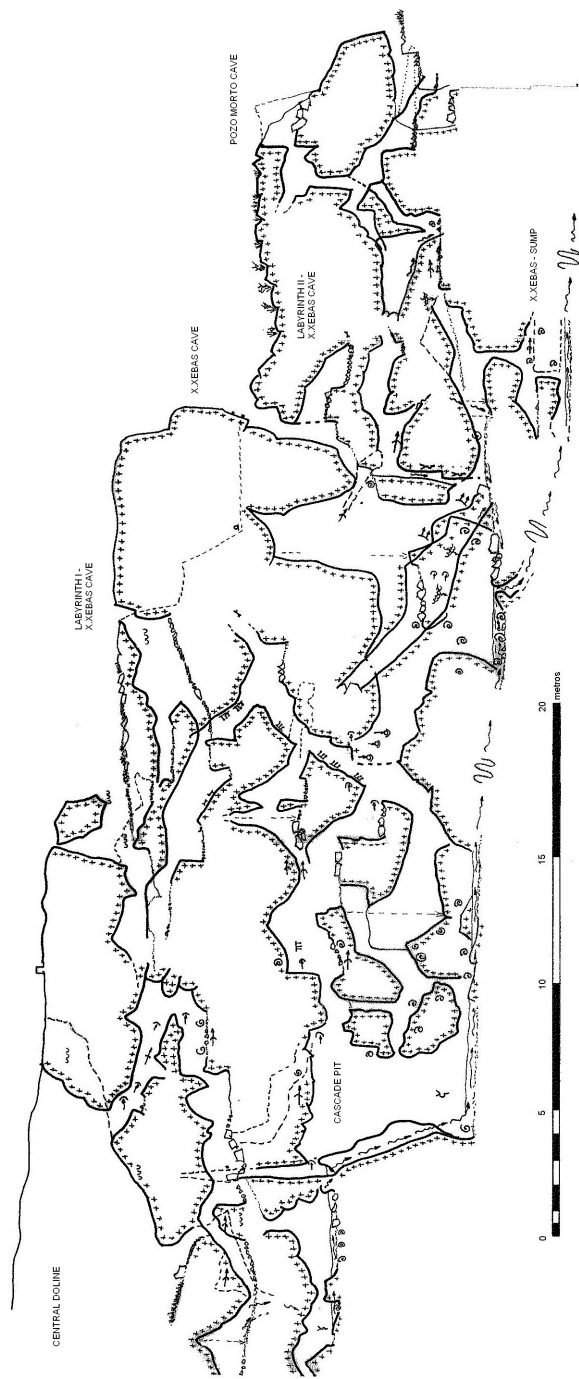


Fig. 7. Cave profile from the studied area. This profile is not a planar plot of cave passages. Passages have been projected over the Riedel planes which determine the cave pattern. It can be observed the present structure of this system between the Central Doline and the X.Xebas Sump. The water carry at the present is remarked with flow marks. They are indicated lateral notches, potholes and disarticulated potholes, weathering forms and speleothemes in their real positions and elevations.

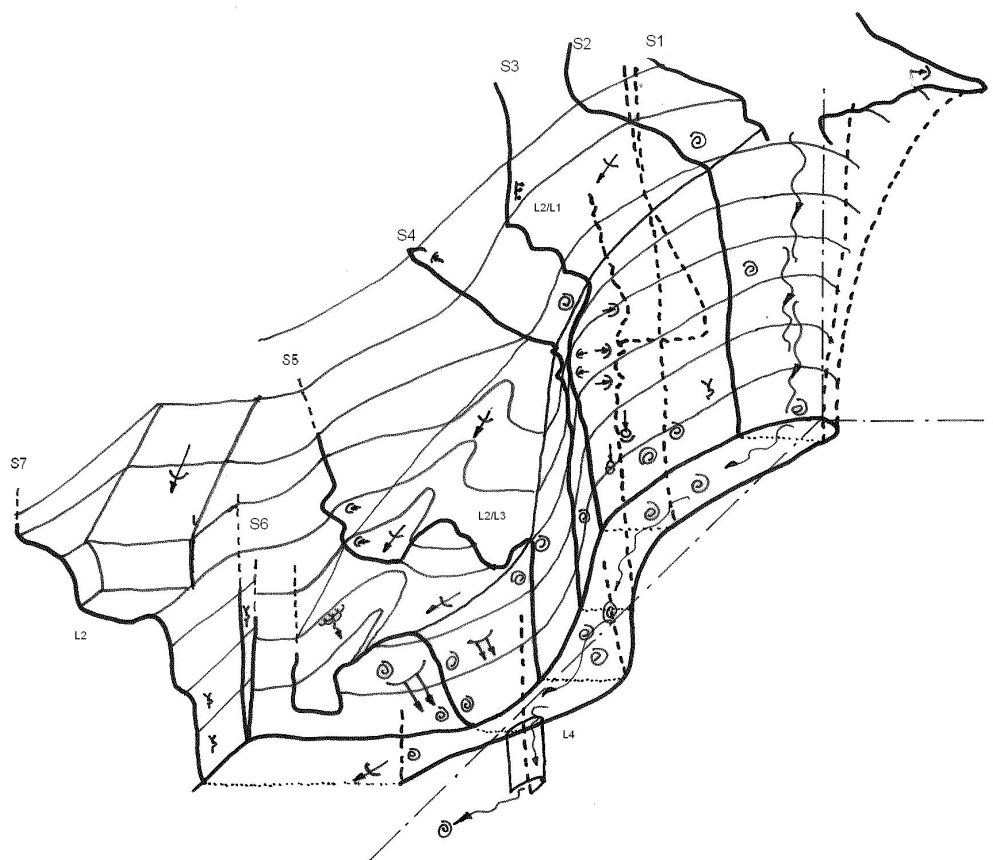


Fig. 8. A 3D perspective of the zone. This plot was made from many individual cross sections in which disarticulated blocks were virtually removed looking only for rocky continuous surfaces. Paleo-flows (fossil passage levels), erosion forms, speleothems and rockslide are indicated. Pseudo-phreatic conducts are located in S3, at the intersection between the upper subhorizontal level (L1-L2) and the middle dipping paleo-level (L2-L3). It may indicate that there was a tap-off passage pirating the flow from this pseudo-phreatic-incised conducts which at present remains isolated above the vadose gutter (L4). Paleo-levels are not pure static levels. They were dynamic levels and in dipping paleo-levels there was not a single transition between them. Rockslide involved many superposed (a vertical succession) of erosion forms. Note that in this projection the relation between horizontal, oblique and vertical axis are (1, fi, 1). The equidistance used to rebuild the surface is 1 m.

The three-dimensional perspective of the zone (fig. 8) shows the relative disposition of the phreatic and vadose conduits and allows the reconstruction of the evolution of the subterranean incision.

The phreatic conduits are located in section S3 hanging over the main vadose conduit. They are very close to the intersection between the upper subhorizontal levels (L1-L2) and the intermediate paleo-levels with incision (L2-L3). They may be interpreted as the result of

the flow capture that drained through the pseudo-phreatic conduits. This would indicate that the paleo-levels were not static but dynamic without simple transition among them.

In this figure it is shown the frontal rockslide (between S5 and S6), including the superposition of erosion forms (fig. 5c and fig. 9) that partially covers the L4 flow. Thus, the flow is sumped into a new diffuse network (anastomosed) developed below the blocks of the slide. The rockslide is now fossilised by sand deposits.



Fig. 9. A detail of a pothole developed between L3 and L4 flow levels.

This view has been made from different cross-sections from which the blocks have been eliminated virtually to show the continuous rock walls only. The paleo-flows (paleo-levels), erosion forms, speleothems and rock-slides have been indicated with their real levels. Note that in this projection the relation among the horizontal, oblique and vertical axes is (1, fi, 1). The equidistance used to form the surfaces has been of 1 m.

## CONCLUSIONS

The development patterns of the conduits in the granitic caves are directly related to the local structure system. The distribution and the geometry of the conduits inside the system depend on the lithology, structure and regime of the water flow through the systems of cavities.

Generally, these conduits present a cross-section of incise channel with development

related to the subvertical fracture planes and the subhorizontal shear bands. The fracturing density of the massif determines the development and evolution of the conduits and facilitates the collapse of the conduits and the related accumulation of smaller blocks and fragments in the available space.

The structures of phreatic-incise and vadose origin, their evolution by continuous incision, as well as the capture processes (flow piracy) are quite similar to the equivalents in the karstic systems s.s..

## ACKNOWLEDGEMENTS

We thank Ana Martelli for reviewing the paper English version and Juan Ramón Vidal for his criticism of the ideas expressed in this paper which helped to improve it. The work and surveys would not have been done without the help of friends in the "Clube Espeleológico Maúxo" - Speleological Association.

*Recibido: 7 / 7 / 2006*

*Aceptado: 9 / 10 / 2006*

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